Design and Control of a Multiple Degree of Freedom Haptic Interface

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Abstract

The role of robotics in society is no longer restricted to assembly and manufacturing. Robots are finding their way into a wide spectrum of tasks that directly link human and machine. Haptic interfaces are robots that are physically coupled to humans and produce desired tactile stimulation. These devices are integrated into active joystick control for aircraft, bilateral teleoperation, robotic assisted surgery and human rehabilitation and training. This paper discusses the design and control of a new haptic interface at the Georgia Institute of Technology. HURBIRT (Human Robot Bilateral Research Tool) is a two degree of freedom planar manipulator used to investigate control issue in teleoperation and human-machine interaction.

Nomenclature

d_{ij} - ij^{th} component of inertial tensor
ϕ_i - gravitational component of i^{th} DOF
τ_i - force of i^{th} DOF
q_i - generalized displacement of i^{th} DOF
m_i - mass of i^{th} link
l_i - length of i^{th} link
l_{ci} - distance to COM of i^{th} link
x - Tip position of manipulator
x_0 - Desired tip position of manipulator
F - Human applied force vector
M - Desired tip inertial tensor
B - Desired tip damping tensor
K - Desired tip stiffness tensor

Introduction

Since the first robots designed in the late 1940's (Goertz, 1952), the integration of human and robot has been a popular research interest. The initial applications focused on assisting humans in remote handle hazardous materials. Ironically, this is still an active research topic. Today, many diverse applications can benefit from the improved integration of human and robot that result from research on haptic interfaces.

The role of robots in human rehabilitation and training was first investigated by Book, et.al. (1979). A manipulator can produce constrained paths to guide the human along desired trajectories. The advantage of such systems is the ability to actively control and record resistance. A multiple degree of freedom system can facilitate a wide range of exercises. For rehabilitation, measurement of human resistance can assist in the isolation and quantification of injuries as well as gage progress. The first prototypes were mechanically and electronically crude. The evolution of computers and mechanical motion systems has renewed interest in this field. One critical issue currently under investigation is the modeling of human resistance. Hollerbach and Kazerooni (1992) discuss the modeling of humans coupled to robots. Horowitz, et.al. (1993) considers a control algorithm that uses self tuning control to optimize the work done by the human.

This paper describes the design and control of a new robot at the Georgia Institute of Technology used for investigating a variety of tasks involving humans coupled to robots. The design takes advantage of the well-documented characteristics of closed kinematic chains. A discussion of current and future work is included.

Robotic Transformer

There are many control issues concerning haptic interfaces that are currently under investigation. The issues span a range of applications that include unilateral and bilateral teleoperation, time delays in teleoperation, exercise physiology, and the coupled stability of human and manipulator. During the design process of HURBIRT, illustrated in Figure 1, an attempt was made to build a robot which could address many of these topics. As an exercise machine, the robot may need to facilitate a workspace optimized for arm and/or leg motion. The mechanical assembly of the links can be easily reconfigured to produce a variety of workspaces. Many teleoperation algorithms are initially tested on a simple single DOF testbed. Figure 2 illustrates how HURBIRT can be configured as a single 2 DOF master arm or two single DOF manipulators. When satisfactory performance is obtained, the system is reconfigured as a 2-DOF master robot.

A project that is currently using HURBIRT consists of teleoperation using long reach manipulators. HURBIRT acts as an active master arm electronically connected using serial communication to RALF(Robot Arm Long and Flexible), an elastic long reach manipulator. Issues under investigation include bandwidth limitations due to control and transmission delays, the role of different cues in training and performance, and the performance of different teleoperation schemes.

A second advantage to the current kinematic design is the use of a closed kinematic chain. One benefit of the closed chain is the ability to remotely drive one of the degrees of freedom. By constraining the lengths of the closed chain to form parallelogram, the kinematics and dynamics are simplified (Spong and Vidyasagar, 1989). This kinematic design constraint eliminates the Coriolis terms in the dynamic equations of motion, Equation (1).

$$\begin{aligned}\tau_1 &= d_{11}\ddot{q}_1 + d_{12}\cos(q_1+q_2)\ddot{q}_2 - \\ &\quad d_{12}\dot{q}_1^2 \sin(q_1+q_2) + \phi_1\cos(q_1) \\ \tau_2 &= d_{22}\ddot{q}_2 + d_{12}\cos(q_1+q_2)\ddot{q}_1 + \\ &\quad d_{12}\dot{q}_2^2 \sin(q_1+q_2) + \phi_2\cos(q_2)\end{aligned} \tag{1}$$

All of the coefficients in the equations of motion are constant. The term d_{12} has special significance in the design and control of the robot. This coefficient is dependent upon the mass properties of the links.

$$d_{12} = m_3 l_2 l_{c3} - m_4 l_1 l_{c4} \tag{2}$$

If the design of the links is such that these properties force the term d_{12} to zero, the dynamic equations of motion for HURBIRT reduce to a set of uncoupled differential equations. The Coriolis and centripetal acceleration, terms common with serial link manipulators, are dynamically canceled. In addition, the coefficients in the inertial tensor are time and state invariant.

$$\begin{aligned}\tau_1 &= d_{11}\ddot{q}_1 + \phi_1\cos(q_1) \\ \tau_2 &= d_{22}\ddot{q}_2 - \phi_2\cos(q_2)\end{aligned} \tag{3}$$

Kazerooni has illustrated that the design of a robot using such a closed kinematic chain can be extended to eliminate the gravitational effects (1989).

Control

A virtual environment is the physical compliment of virtual reality. In virtual reality, the human receives visual stimulation via a computer generated image. If all works well, the human will feel like he is in the virtual environment. Haptic interfaces attempt to do the same thing, but with tactile or physical stimulation. A human coupled to one such device will physically feel like he is doing work or maneuvering around some computer generated environment. A robot is the ideal tool to produce this stimulation. As with all robots, an open question to answer is what type of control algorithm best suits this application.

There are a variety of manipulator control techniques. These control schemes directly affect the performance of a robot when coupled to a human. General motion control techniques are based upon a desired robot trajectory. Any external forces applied to the manipulator are treated as disturbances. A good motion controller rejects these external forces. Likewise, force control techniques attempt to control the robot so that it produces a desired force at its end effector. To select the appropriate control strategy for a haptic interface, the objective or goal for the device must be specified.

A good haptic interface should be able to simulate a range of target dynamic systems. Impedance control techniques naturally produce this effect (Hogan, 1985). Consider the popular form for the dynamic equations of motion for a n-link rigid robot.

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + J^t F \qquad (4)$$

The goal of an impedance control algorithm is to force the robot to behave like a target dynamic system. Assume that this target system takes the form of a simple spring-mass-dashpot.

$$M\ddot{x} + B\dot{x} + K(x-x_0) = F \qquad (5)$$

The design of the control algorithm consists of identifying the torque required to eliminate the dynamics of the robot while forcing the manipulator to behave as the target dynamic system. The desired acceleration of the tip of the robot is a function of the external force vector and the target dynamics.

$$\ddot{x} = M^{-1}\ [\ F - B\dot{x} - K(x-x_0)] \qquad (6)$$

The Jacobian transformation maps the resultant acceleration from the space of the target dynamics to the generalized coordinates of the robot.

$$\dot{x} = J(q)\dot{q} \qquad (7)$$

$$\ddot{x} = J(q)\ddot{q} + \dot{J}(q)\dot{q} \qquad (8)$$

The acceleration vector in the generalized coordinates is defined by combining Equations (6) and (8).

$$\begin{aligned}\ddot{q} = {} & J^{-1}(q)M^{-1}[F-B\dot{x}\ K(x-x_0)] \\ & -J^{-1}(q)J(q)\dot{q}\end{aligned} \qquad (9)$$

The torque required to force the robot to behave like the target dynamic system is expressed in Equation (10).

$$\begin{aligned}\tau = {} & \hat{D}(q)J^{-1}(q)\ M^{-1}\ [F - B\dot{x} - K(x-x_0)] \\ & -\hat{D}(q)J^{-1}(q)J(q)\dot{q} + \hat{C}(q,\dot{q})\dot{q} \\ & +\hat{g}(q) - J^t(q)F\end{aligned} \qquad (10)$$

This control scheme can easily be extended to simulate physical environments. The target dynamics can be state and/or time dependent parameters that represent the virtual environment. As the human maneuvers the tip of the robot, the state of the manipulator is used to identify target impedance associated with that location in the artificial environment.

An example of one such environment is a virtual wall. Stanley and Colgate (1992) points out that these types of constraints are ubiquitous in the real world. The designer defines a topology for the manipulators workspace that consists of position dependent impedances. As the human manipulates the robot through the space of the virtual environment, the target dynamics of the manipulator change. If the human moves into the wall, the target stiffness normal to the wall is high. One limitation of this type of virtual environment is that an undesirable vibration persists at the boundary of the wall. Future work will investigate various methods to adapt the impedance control algorithm not only to variations in the target impedance, but the operator as well.

Hardware and Software Implementation

To carry out the computations required for the control of the robot, a DSP chip (TI TMS320C25) based computer, by DSpace Inc., is used. Implied in this control algorithm, Equation (10), is the calculation of sine, cosine, in addition to the standard product and sum of states of the robot. The motion and external forces of the robot, q1, q2, Fx, and Fy respectively, must be read from a transducer interface. The resulting torques must then be commanded from the motors.

DSP chips are very efficient at linear computations which consist of multiplies and adds. To calculate nonlinear terms such as sine and cosine, a lookup table is formed using the capabilities of DSpace's NMAC25 software module. A table is initially generated using a secondary software package such as Matlab or Mathematica. NMAC25 imports the table and transforms it into assembly code which is linked with the C or DSPL code of the controller. Furthermore, the TMS320C25 is a fixed point chip. The speed and cost of the chips, critical in control implementation, are superior to floating point processors but require careful numerical scaling to avoid numerical overflow.

The control algorithm was programmed using the DSPL language developed by DSpace, Inc. This package attempts to encourage the programmer to form computational loops which consist of vector and matrix multiplications. The compiler interprets these matrix and vector manipulations to optimize the single cycle multiply and accumulate capabilities of the processor. The entire servo loop which consists of reading 4 A/D channels, 2 encoder channels, writing 2 D/A channels as well as the computation of the robot command torques runs at a frequency of 1000 Hz. This uses approximately 15% of the available computation time. Future work will use this excess time for identification of human and/or environment dynamics.

The DSP Board and accompanying data acquisition components, are placed in a host AT Bus computer. The 80486 computer is available to serve as an interface between the servo controller and the human involved in the experiments. RAM on the DSP board is directly accessible to the 80486. Controller gains and target impedance values can be changed "on the fly" from the keyboard.

Impedance Simulations

Initial experiments are directed towards identifying the accuracy of the tactile simulation. The target impedance of the robot in the initial experiments consists of a potential well. An equilibrium point is set at the coordinates x=0.6096 m and y=0.6096 m. As a human pushes on the handle, the target impedance consists of a mass of 5 kg, stiffness of 233 N/m and damping of 68.3 N-s/m. Figure 4 illustrates the resulting force and motion profiles of a human randomly pushing on the robot. To quantify the accuracy of the impedance controller, a state space representation of the target impedance is modeled in Matlab with the human applied forces supplied as the input. The resulting simulated motion is compared to the actual tip motion of the robot, illustrated in Figure 5.

One important consideration to make is that the controller only computes the torque required to eliminate the modeled dynamics of the manipulator and force it to behave like the target impedance model. There is no inner servo control loop for the position and/or velocity of the robot. The advantage of such a control scheme is that the "feel" of the robot is independent of any servo control gains. The disadvantage is the reliance upon high accuracy of parametric and nonparametric modeling of the manipulator. One possible resolution to this problem would be to augment the impedance control algorithm with an inner identification loop which attempts to identify the dynamic characteristics of the manipulator in real-time

Conclusion

The field of robotics is no longer limited to basic assembly and manipulation tasks. Robots are finding their way into more complex and demanding tasks, many of which couple the active manipulator to a human operator. This adds to the complexity of the dynamics and control of such devices. A system has been developed at Georgia Tech that will assist in investigating many of the control problems that currently exist with such systems.

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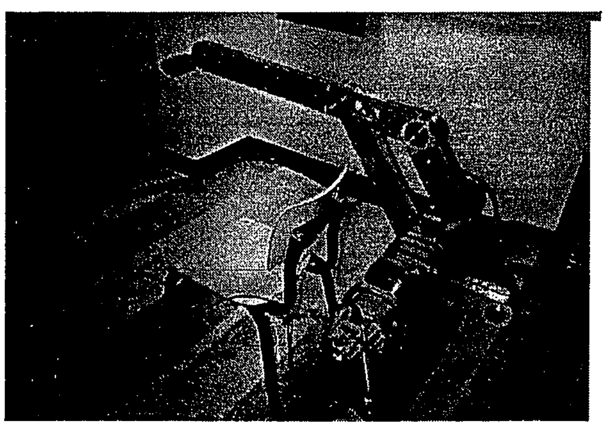

Figure 1: HURBIRT

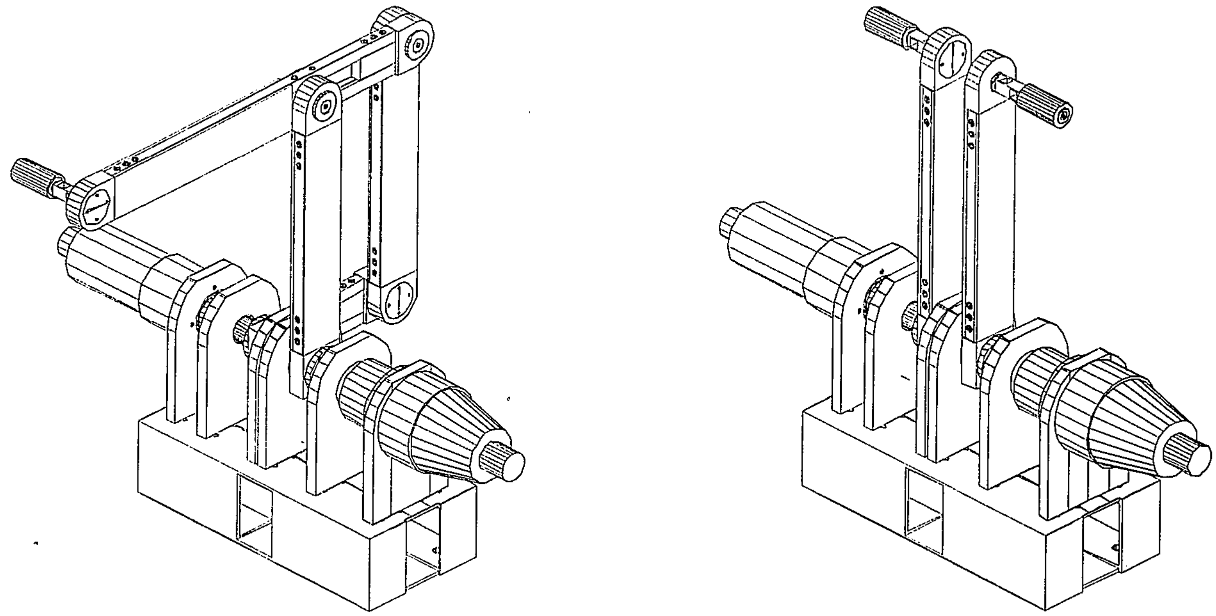

Figure 2: HURBIRT Configurations

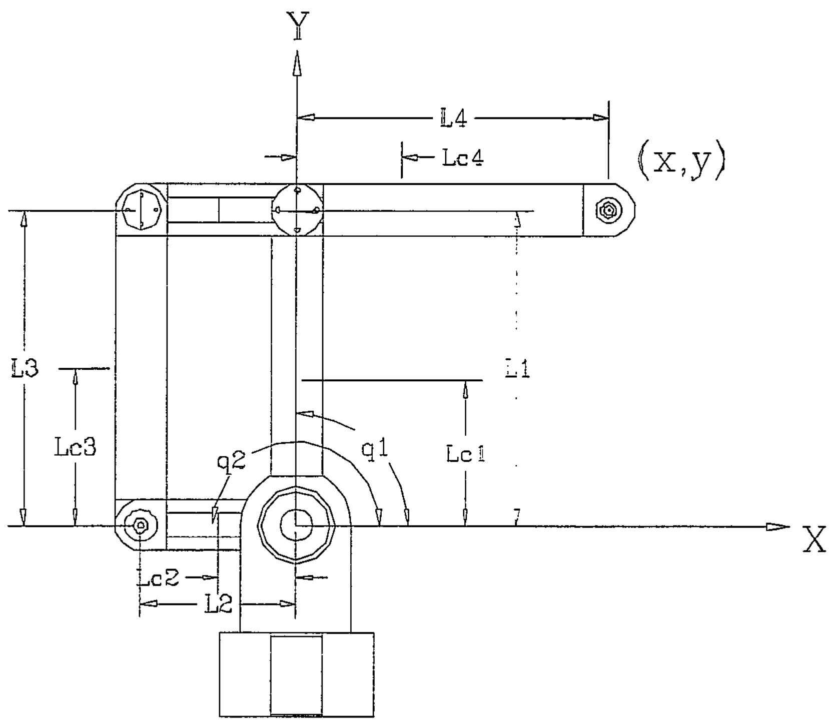

Figure 3: Kinematics of Herb

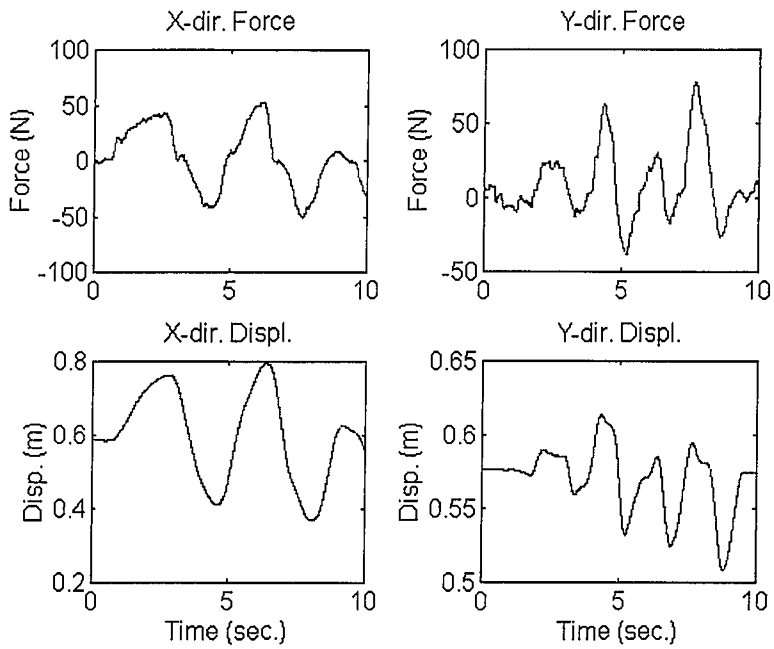

Figure 4: Force and Displacement Profiles

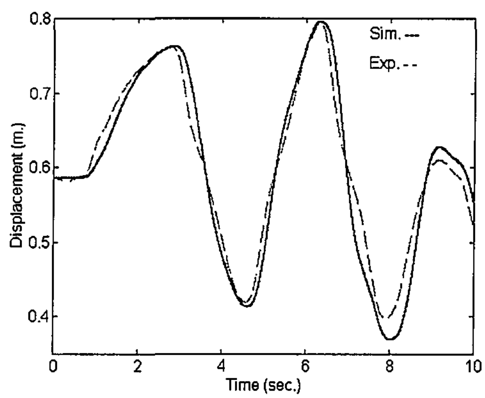

Figure 5: Experimental and Simulated Tip Motion To Human Applied Force

Link	L (m)	L_c (m)	mass (kg.)	I (kg-m^2)
1	0.6906	0.2337	7.0280	0.3116
2	0.3048	0.1025	4.5394	0.0611
3	0.6096	0.2991	6.8740	0.3578
4	0.6096	0.2455	8.5605	0.8646

Table 1: Robot Parameters